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Synchronization, retiming and time-division multiplexing of an asynchronous 10 Gigabit NRZ Ethernet packet to terabit Ethernet

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Abstract: An asynchronous 10 Gb/s Ethernet packet with maximum packet size of 1518 bytes is synchronized and retimed to a master clock with 200 kHz frequency offset using a time lens. The NRZ packet is simultaneously converted into an RZ packet, then further pulse compressed to a FWHM of 400 fs and finally time-division multiplexed with a serial 1.28 Tb/s signal including a vacant time slot, thus forming a 1.29 Tb/s time-division multiplexed serial signal. Error-free performance of synchronizing, retiming, time-division multiplexing to a Terabit data stream and finally demultiplexing back to 10 Gb/s of the Ethernet packet is achieved.

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1. Introduction

Terabit Ethernet interfaces that aggregate traffic from several 10 Gb/s Ethernet links into a serial Terabit optical data stream are promising for future ultra-fast communication networks. Time-division multiplexing (TDM) is an effective technology for building ultra-high speed networks, which has been demonstrated at a symbol rate of 1.28 Tbaud on a single wavelength [1–3]. As Ethernet packets are asynchronous in nature but a TDM system based on bit interleaving is synchronous, the Ethernet packets in each link have to be synchronized to a master clock in the Terabit Ethernet interfaces and then time division multiplexed into a serial Tb/s data stream.

In order to interface between asynchronous Ethernet networks and bit-interleaved synchronous high-speed TDM networks, a number of challenges need to be addressed, such as packet sizes varying from 64 to 1518 bytes (according to Ethernet standard IEEE 802.3), repetition rate variations, timing jitter reduction, non-return-to-zero (NRZ) to return-to-zero (RZ) format conversion and data pulse compression. According to the protocol of 10 GE WAN PHY, the repetition rate of each Ethernet packet can vary with up to ± 20 ppm of the nominal transmission rate, i.e. ± 200 kHz frequency offset between transmitter and receiver must be tolerated [4,5].

In this paper, we demonstrate, based on a time lens, that an asynchronous Ethernet packet with the maximum standardized size of 1518 bytes can be synchronized and retimed to a master clock with 200 kHz frequency offset. In addition, the input packet with NRZ format is simultaneously converted to an RZ format, and then compressed into short data pulses with a pulse width of 400 fs, and finally optical time-division multiplexed (OTDM) with a serial 1.28 Tb/s RZ-OOK signal having a vacant time slot. The multiplexed Ethernet packet is received in an OTDM receiver triggered by the master clock and error-free performance of the demultiplexed Ethernet packet is achieved.

2. Operation principle of a time lens

The concept of a time lens stems from the time-space duality, which refers to the analogy between the paraxial diffraction of beams through space and the dispersion of narrowband pulses through dielectric media in time [6–12]. Since a spatial lens can be used to obtain the Fourier transform of a spatial profile at the spatial focus, a time lens can also be used to obtain the Fourier transform of a temporal profile at the temporal focus. In Fourier analysis, any time shift or timing jitter only change the phase in the frequency domain but does not change the envelope, which can be expressed as $x(t - n\Delta T - \delta t) \leftrightarrow X(\omega)e^{-j\omega(n\Delta T + \delta t)}$. The asynchrony of the incoming packet can be viewed as a time wandering or time shift of the packet pulses relative to the local master clock. Hence, after the Fourier transform these time shifts can be transferred into frequency domain. If we only detect the envelope of the electrical field in time domain but discard the phase of the electrical field, the time wandering or time shift can be removed. Therefore, we can use the time lens to cancel the time wandering caused by the asynchrony and also to reduce the timing jitter.

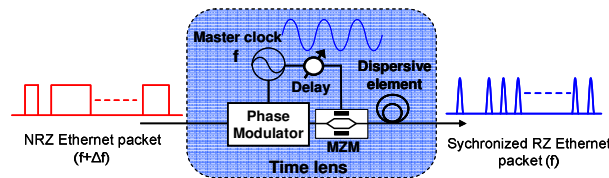


Fig. 1. Schematic of synchronization and NRZ-to-RZ conversion of Ethernet packets, based on a time lens.

A time lens could be any device that imposes a quadratic phase in time onto an incoming electrical field. The time lens in this experiment consists of a cascaded phase modulator and Mach-Zehnder modulator (MZM) followed by a piece of fiber as the dispersive element, as shown in Fig. 1. The phase modulator is driven by a sinusoidal signal, which locally approximates a quadratic phase modulation. The MZM is used to remove the part of the waveform subjected to the lower part (concave) of the sinusoidal phase modulation (corresponding to positive chirp) and to only keep the waveform part overlapped with the upper part (convex) of the sinusoidal phase modulation (corresponding to negative chirp), as a result of Fig. 2 (a). The dispersive element (dispersion compensating fiber (DCF) in this experiment) provides the temporal focus in the system. In addition, all the bits in the packet experience negative chirp and can be compressed into short pulses in the DCF, which in turn allows converting an NRZ signal into an RZ signal.

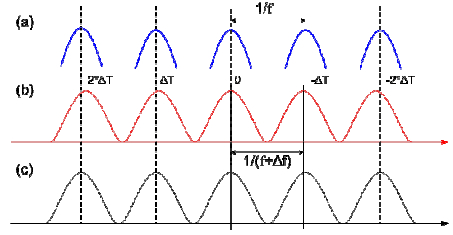


Fig. 2. Operation principle of the synchronization and retiming based on a time lens. (a) phase modulation (blue, Y-axis is power of phase); (b) packet data pulse before the synchronization; (c) packet data pulse after the synchronization (black, Y-axis is power of amplitude).

The time lens scheme can also be understood from the chirp point of view, as shown in Fig. 2. If the input signal pulse with the repetition rate of $f + \Delta f$ is aligned with the center of the phase modulation with the repetition rate of f , it experiences relatively zero chirp since the time derivative of the phase modulation is zero. However, the input signal on the right side of the central data pulse will experience the relatively negative chirp and the input signal on the left side will experience the relatively positive chirp. The signal which is farther away from the central data pulse will have more chirp. If they pass through a dispersive element and the chirp is removed, all the data pulses will move to the center of the phase modulation and the initial temporal misalignment will thereby be removed in time domain, as shown in Fig. 2 (c).

If the timing shift between the phase modulation and input signal is $n\Delta T$ and the timing jitter is δt , the sinusoidal phase modulation can be expressed as

$$\Delta\varphi = \pi \frac{V_{pp}}{2V_{\pi}} \cos[\omega_m(t + n\Delta T + \delta t)] \quad (1)$$

where V_{pp} is the peak-to-peak driving voltage, V_{π} is the driving voltage to achieve a π phase shift, ω_m is the angle frequency of the master clock, $n \in [-k, k]$. Expanding $\Delta\varphi(t)$ near $t = 0$ and ignoring the constant phase term, $\Delta\varphi(t)$ can be expressed as

$$\Delta\varphi \approx -\pi \frac{V_{pp}}{4V_{\pi}} \omega_m^2 (t + n\Delta T + \delta t)^2 \quad (2)$$

We can also get the frequency shift as a function of the timing shift, as shown below

$$\Delta\omega = \pi \frac{V_{pp}}{2V_{\pi}} \omega_m^2 (n\Delta T + \delta t) \quad (3)$$

If the signal passes through a dispersion element, the timing shift caused by the central frequency shift can be expressed as

$$\Delta t = \Delta\omega\beta_2 L = \pi \frac{V_{pp}}{2V_{\pi}} \omega_m^2 (n\Delta T + \delta t)\beta_2 L \quad (4)$$

To eliminate the timing shift and reduce the timing jitter, it's required that

$$\Delta t = -(n\Delta T + \delta t) \quad (5)$$

then, we can get the dispersion amount as

$$\beta_2 L = \frac{-2V_\pi}{\pi V_{pp} \omega_m^2} \quad (6)$$

or

$$DL = \frac{4CV_\pi}{\lambda^2 V_{pp} \omega_m^2} \quad (7)$$

where C is the speed of light in vacuum.

3. Experimental setup

Figure 3 shows the experimental setup for the time lens based 10 G Ethernet packet synchronization and retiming, and subsequent OTDM with a serial 1.28 Tb/s signal including a vacant time slot. The setup includes a 10 G Ethernet packet generator, an optical packet synchronizer and retimer, a pulse compressor, a multiplexer, a 1.28 Tb/s OTDM RZ-OOK transmitter and an OTDM receiver. A continuous wave (CW) light at 1556 nm is encoded by NRZ on-off keying (OOK) using software defined pattern to generate 10 Gb/s Ethernet packets and the bit pattern generator (BPG) is driven by an asynchronous clock of 9.9534 GHz. As shown in Fig. 3, the Ethernet packet consists of a preamble, a destination address, a source address, an Ethernet type, payload data and a frame check sequence (FCS). The maximum standardized size of 1518 bytes with a packet repetition rate of 100 kHz is generated in the BPG, and the waveform is shown in the inset of Fig. 3.

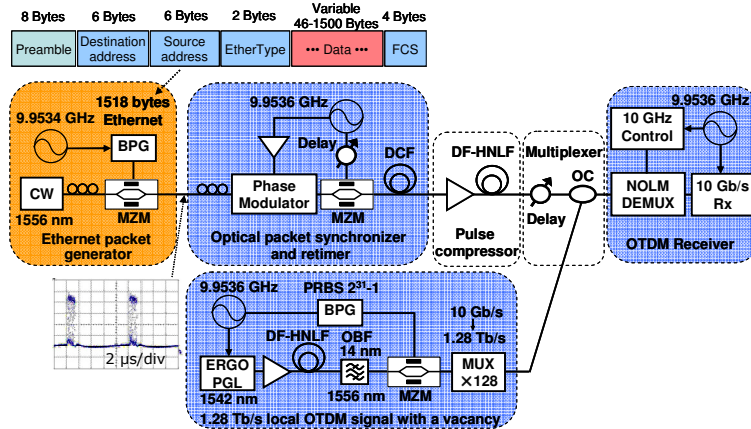


Fig. 3. Experimental setup for time lens based 10 G Ethernet packet synchronization and retiming, then subsequent optical time division multiplexing with a serial 1.28 Tb/s signal.

In the optical packet synchronizer and retimer, the 10 G Ethernet packet is launched into a cascaded phase modulator (modulation depth of 4π) and MZM, both driven by the master clock of 9.9536 GHz (200 kHz offset from the input clock), and then launched into a 400 m DCF. As described above, the time-domain optical Fourier transform (OFT), or equivalently the time lens effect, can be obtained after the DCF. The incoming packet is aligned with the master clock in order to make sure that the whole packet be processed is within the same period of the phase modulation, i.e. the time wandering of the packet data should be no more than one bit period. In this case, the 10 G input asynchronous Ethernet packet with the data rate of 9.9534 Gb/s is converted into a synchronized Ethernet packet with the data rate of 9.9536 Gb/s. At the same time, the Ethernet packet is format converted into an RZ signal with a full width at half maximum (FWHM) of 6 ps. Additionally, the converted RZ signal is further pulse compressed to a FWHM of 400 fs in a 500 m dispersion-flattened highly

nonlinear fiber (DF-HNLF, dispersion coefficient $D = -1.11$ ps/(nm·km) and dispersion slope $S = 0.0056$ ps/(nm²·km) at 1550 nm, nonlinear coefficient $\gamma \sim 10$ W⁻¹km⁻¹).

In the 1.28 Tb/s RZ-OOK transmitter, which is synchronized to the master clock of 9.9536 GHz, a pulse train with a repetition rate of 9.9536 GHz is generated from an erbium glass oscillating (ERGO) laser and then compressed to 370 fs in a 400 m DF-HNLF ($D = -0.45$ ps/nm/km, $S = 0.006$ ps/nm²/km at 1550 nm, $\gamma = 10.5$ W⁻¹km⁻¹) [1]. The compressed pulses are OOK modulated by a 9.9536 Gb/s PRBS ($2^{31}-1$) in a MZM. The modulated RZ-OOK signal is multiplexed in time to 1.28 Tb/s including a vacant time slot using a passive fiber delay multiplexer (MUX $\times 128$), as shown in Fig. 5 (b). The synchronized and pulse compressed Ethernet packet is positioned into the vacant time slot of the 1.28 Tbit/s OTDM signal through a 20 dB optical coupler (OC), aggregating a serial 1.29 Tbit/s OTDM signal, as shown in Fig. 5 (c).

In the receiver, which is also synchronized to the master clock of 9.9536 GHz, a nonlinear optical loop mirror (NOLM) is used to demultiplex the 10 G Ethernet packet from the high speed serial data stream. The NOLM operation is based on cross-phase modulation (XPM) in a 50 m HNLF. The control pulse is at 1533 nm and has a pulsewidth of 470 fs. Finally, the demultiplexed 10 G Ethernet packet is detected by a 10 Gb/s receiver and measured by an oscilloscope and an error analyzer, which are both triggered by the master clock.

4. Experimental results

We first measured the electrical power spectrum of the synchronized packet and compared it with the spectrum of the input packet before the synchronization and the NRZ-to-RZ conversion, as shown in Fig. 3. The 100 kHz spaced peaks are due to the packet repetition rate. We can see that the maximum frequency peak of the synchronized packet has been shifted from the input clock of 9.9534 GHz to the master clock of 9.9536 GHz.

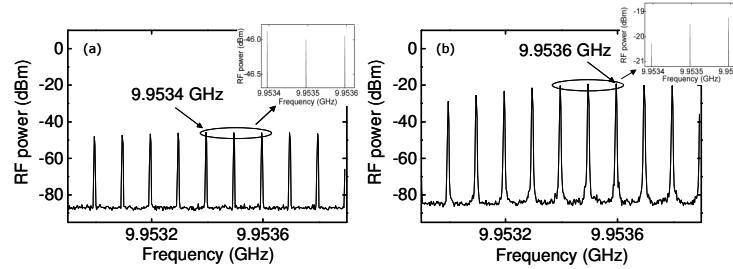


Fig. 4. (a) Electrical power spectrum of the input NRZ packet; (b) the synchronized RZ packet. Insets: zoom in of the electrical power spectrum.

Figure 5 (a) inset shows the eye diagram for the input NRZ packet when the oscilloscope is triggered by the original clock (9.9534 GHz), which has a timing jitter of ~ 6 ps. Figure 5 (a-c) show eye diagrams for the synchronized, retimed and compressed RZ packet, and the Tb/s serial signal before and after the addition of the synchronized 10 G Ethernet packet, when the optical sampling oscilloscope (OSO) is triggered by the master clock (9.9536 GHz). The clear eye diagram shown on the oscilloscope (Fig. 5 (a)) indicates the packet has been synchronized to the master clock with strongly reduced timing jitter. The packet data pulse with a pulsewidth of 400 fs (measured by an autocorrelator) seems to be broader on the OSO due to the limited resolution of 1 ps. Figure 4 (c) shows that the 10 G Ethernet packet is successfully synchronized and correctly positioned into a time slot in the aggregated serial 1.29 Tb/s signal. The Tb/s signal seems to be overlapped with each other, which is mainly due to the limited resolution (~ 1 ps) of the sampling oscilloscope and also partly because of the residual pedestal of the data pulses.

As shown in Fig. 6 (a), bit error rates (BER) are measured for the input NRZ packet, synchronized and compressed RZ packet and demultiplexed RZ packet from the aggregated

1.29 Tb/s OTDM signal and also from the aggregated 650 Gb/s OTDM signal when the receiver is triggered by the master clock. Figure 6 (b) and (c) show the eye diagrams for the

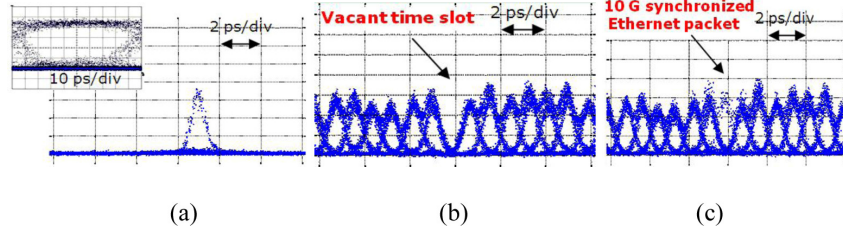


Fig. 5. (a) Optical sampling oscilloscope diagrams of the 10 Gb/s synchronized, retimed and compressed RZ packet ; (b) the 1.28 Tb/s OTDM serial signal with a vacant time slot ; (c) the synchronized Ethernet packet multiplexed with the 1.28 Tb/s signal. Inset: 10 Gb/s input NRZ packet.

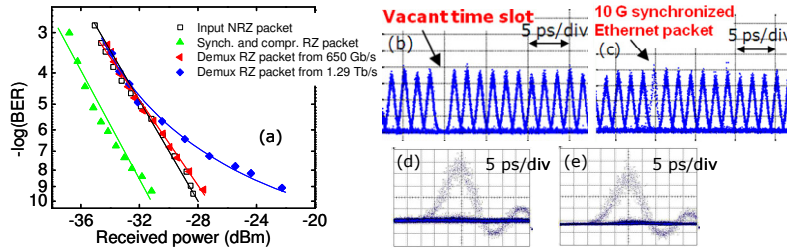


Fig. 6. (a) BER measurements for the input NRZ packet, synchronized and compressed RZ packet and demultiplexed RZ packet from the aggregated 650 Gb/s and 1.29 Tb/s OTDM signal; (b) the 640 Gb/s OTDM signal with a vacant time slot; (c) the aggregated 650 Gb/s OTDM signal with the 10 G synchronized Ethernet packet; (d) and (e) demultiplexed eye diagrams of the RZ packet from the aggregated 650 Gb/s OTDM signal and 1.29 Tb/s OTDM signal, respectively.

640 Gb/s signal including a vacant time slot and the aggregated 650 Gb/s OTDM signal. Compared to the input NRZ packet, the synchronized and compressed RZ packet has 3.1 dB negative power penalty which is the expected benefit from the NRZ-to-RZ format conversion [13]. Compared to the synchronized RZ packet, the demultiplexed RZ packet from aggregated 650 Gb/s OTDM signal and 1.29 Tb/s OTDM signal has an additional power penalty of 3.8 dB and 8.7 dB at the BER of 10^{-9} , after the multiplexing and demultiplexing. Figure 5 (d) and (e) show the eye diagrams of the demultiplexed RZ packet from the aggregated 650 Gb/s OTDM signal and 1.29 Tb/s OTDM signal, respectively. The pulse compressed 10 G Ethernet packet has a pedestal which distorts the adjacent OTDM channels, but the pedestal could be removed by passing through an off-center filtered pulse regenerator [1].

5. Conclusion

We have demonstrated that an Ethernet packet with the maximum standardized packet size of 1518 bytes can be synchronized and retimed to a master clock with 200 kHz frequency offset (corresponding to 20 ppm) and at the same time be format converted from NRZ to RZ. Subsequently, the synchronized RZ Ethernet packet is further pulse compressed and multiplexed in time with a 1.28 Tb/s or a 640 Gb/s OTDM signal having a vacant time slot, then aggregated to a 1.29 Tb/s or a 650 Gb/s serial signal, respectively. The scheme does not require any packet clock recovery, although the initial alignment between the incoming packet and the master clock is required which could be done in practical by using a packet envelope detector. Error free performance of synchronizing, retiming, multiplexing with a 1.28 Tb/s or 640 Gb/s OTDM signal and finally demultiplexing back to 10 Gb/s of this Ethernet packet is achieved.

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